

**AUTOMATED FIBER PLACEMENT COMPOSITE MANUFACTURING:  
THE MISSION AT MSFC'S PRODUCTIVITY ENHANCEMENT COMPLEX**

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**ABSTRACT**

Automated fiber placement is a manufacturing process used for producing complex composite structures. It is a notable leap to the state-of-the-art in technology for automated composite manufacturing. The fiber placement capability was established at the Marshall Space Flight Center's (MSFC) Productivity Enhancement Complex in 1992 in collaboration with Thiokol Corporation to provide materials and processes research and development, and to fabricate components for many of the Center's Programs. The Fiber Placement System (FPX) was developed as a distinct solution to problems inherent to other automated composite manufacturing systems. This equipment provides unique capabilities to build composite parts in complex 3-D shapes with concave and other asymmetrical configurations. Components with complex geometries and localized reinforcements usually require labor intensive efforts resulting in expensive, less reproducible components; the fiber placement system has the features necessary to overcome these conditions. The mechanical systems of the equipment have the motion characteristics of a filament winder and the fiber lay-up attributes of a tape laying machine, with the additional capabilities of differential tow payout speeds, compaction and cut-restart to selectively place the correct number of fibers where the design dictates. This capability will produce a repeatable process resulting in lower cost and improved quality and reliability.

**INTRODUCTION**

A rather unique situation exists at the Productivity Enhancement Complex (PEC) in that NASA engineers and scientists work together with industry and university experts to solve material and process problems and perform advanced research and development. Each of the research cells is designed to concentrate on a specific materials need, a specific process or set of related processing activities. This arrangement allowed us to combine the new fiber placement capability with existing filament winding, tape laying, tape wrapping, pultrusion and ancillary facilities.

Developing manufacturing technology is one of the most important challenges in the field of composites. The need exists to establish manufacturing methods that meet the requirements of both superior material properties and program economics. Fabrication of components using composite materials prompts two primary catalysts for our research and development initiatives: the characterization/optimization of the composite processes and fabrication of components for the many projects throughout the Center. To characterize and optimize the process, we must first understand and define the critical parameters involved. To do this, we use a design of experiments statistical methods that will evaluate the available data and provide an understanding of the interactive effects of these parameters. From this understanding, we are able to sustain a repeatable process resulting in lower cost, improved quality and reliability and enhanced performance. We will achieve a process that we can control and provide ourselves and industry alternative solutions for materials and processing selection. At the MSFC we also have an advantage over industry in that we are not under the gun to meet production schedules with this equipment. We can develop and implement improvements without interruption and not just hold the status-quo. The second impetus mentioned was to fabricate components for the Center's programs. Working with the Program offices, the Science and Engineering Organizations, the Technology Utilization Office, and others, we provide very sophisticated flight components, lightweight robotic end effectors, or simpler secondary structures, brackets and fixtures.

## THE FIBER PLACEMENT SYSTEM MECHANICS

The fiber placement system is shown as it is located at the PEC in Figure 1. Fiber placement represents one of the key elements of composite manufacturing technology and is a result of efforts to improve and merge capabilities from filament winding, tape laying, robotics and machine tool rigidity. The fiber placement process utilizes unidirectional prepreg tow material that is applied by compressing the tow material between a roller and part mandrel during movement of the machine and/or mandrel. The fiber placement machine is robotically programmed to maintain the compaction roller on the mandrel. With linear and rotational motions and the capability to vary the number of tows it can precisely place material onto complex surfaces. Repeated application of the composite material onto the mandrel and underlying layers is continually compacted by the roller, thus forming a consolidated laminate.

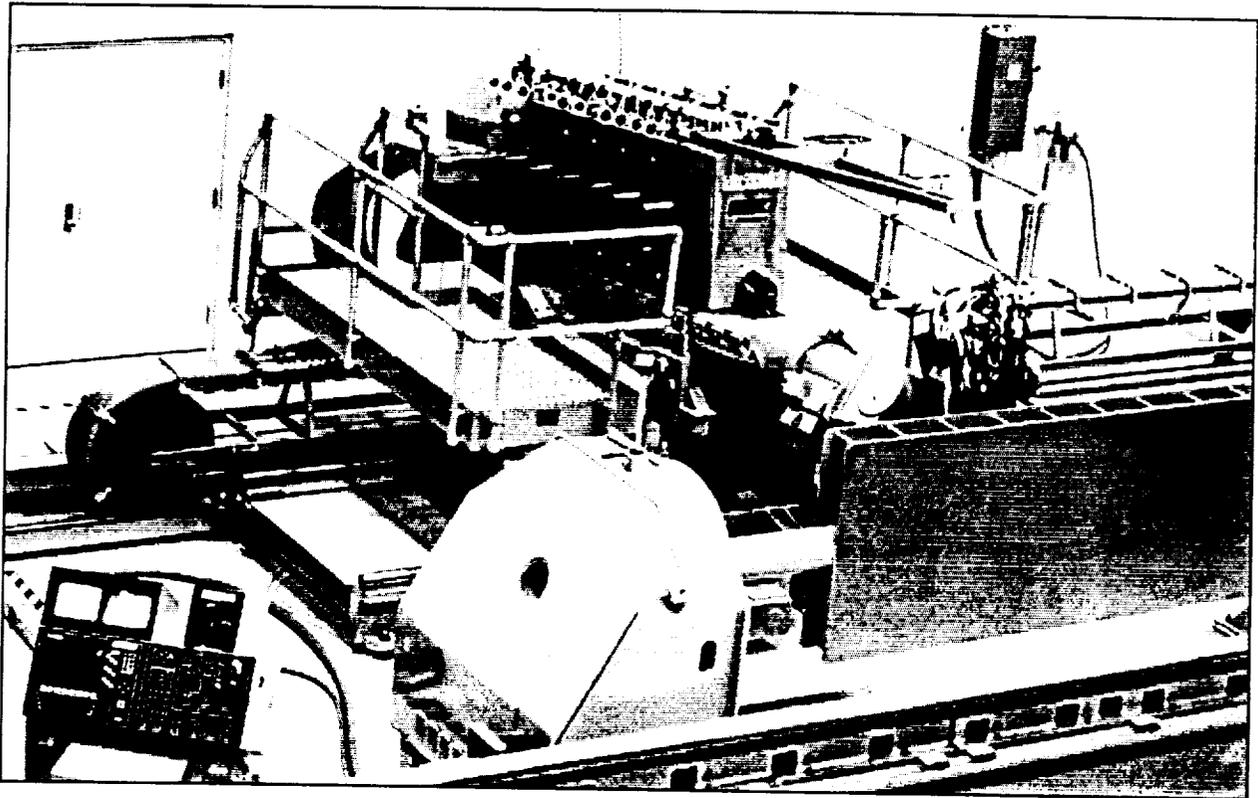
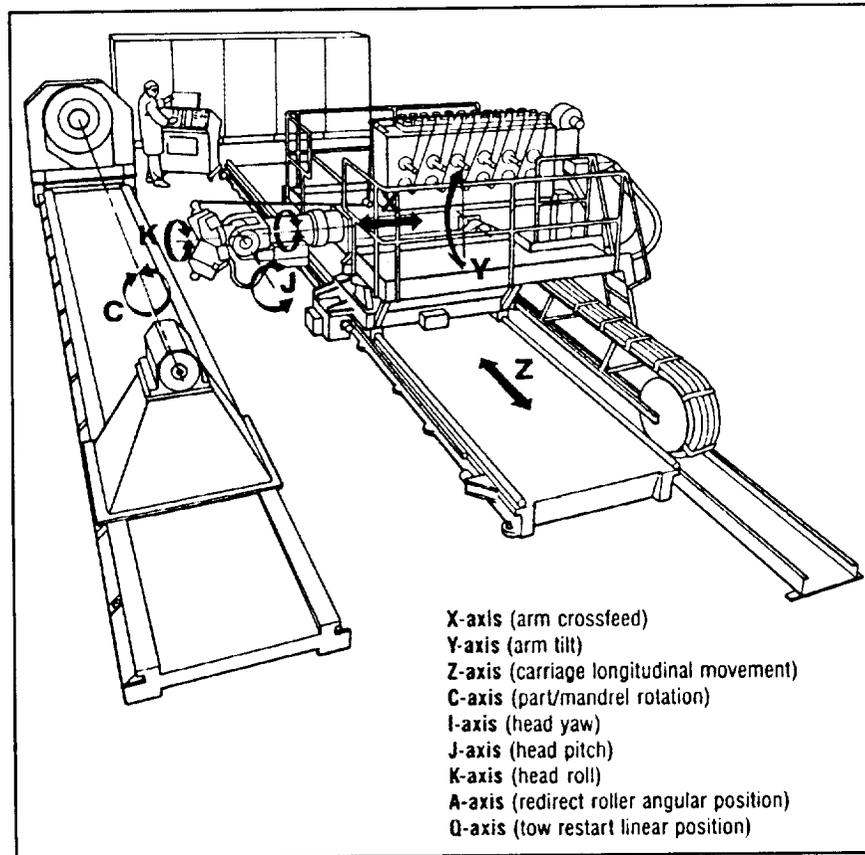


FIGURE 1. VIEW OF THE FPX

The FPX machine has seven major axes of motion as shown in figure (2). It is computer numerically controlled (CNC). The carriage and bed have two linear axes ( $X$  and  $Z$ ) and a tilt axis ( $Y$ ). The mandrel is located parallel to the carriage and has rotational motion ( $C$  axis). The head is attached to the robotic wrist that is capable of three axes of motion: yaw ( $I$ ), pitch ( $J$ ), and roll ( $K$ ). All of the machine axes are employed to keep the compaction roller normal to the mandrel surface.

The machine is capable of applying up to 24 individual tows at a time producing 3-inch wide collimated fiber array. The tow material is delivered from a creel located on the crossfeed bed and equipped with bi-directional tensioners capable of retracting material to avoid slack as the machine moves through its motions. The tows course through guide rollers to a servo-controlled redirect roller located on the head to maintain fiber alignment throughout the machines motions. Certainly, the most sophisticated component of the machine is the delivery head. The computer controlled delivery head precisely dispenses, cuts, clamps, and restarts tow material automatically. The fiber array travels from the redirect roller to the cut/clamp/restart mechanism (CCR). The CCR's are where individual tows are cut to drop off segments of the array, and restarted to resume that segment of the array. To maintain the proper adhesive characteristics (tack), heating and cooling sources are strategically located within the head. The machine is capable of holding parts which are 84 inches in diameter, 342 inches long, and 20,000 pounds.



**FIGURE 2. SEVEN MAJOR AXIS OF MOTION**

Machine control is achieved with Milacron's Acramatic 975F CNC. The control system uses 32-bit buss type open architecture incorporating two 386 processors, two 387 processors, and nine 186 processors to provide high speed instantaneous control to 86 distinct mechanical and pneumatic devices. SDRC's *I-DEAS*<sup>TM</sup> software is used to provide a complete offline programming system to implement a comprehensive mechanical design automation system. The system software is integrated for design, analysis, and manufacturing. A solid model is generated to provide a complete 3-dimensional product definition that can be easily analyzed to determine component performance and manufacturing parameters. Engineering analysis is performed directly from this model as is a manufacturing simulation. Using this approach, alternative designs are optimized to meet established engineering and manufacturing criteria. Productivity is substantially enhanced using this topdown integrated manufacturing strategy. Design, analysis, simulation, machine programming, and data management are all administered from within one software environment.

## THE FIBER PLACEMENT PROCESS

The prevailing method for producing composite components with highly complex geometries is by manual layup. Manual layup of these components is simply not productive and until now, the automated machines available for manufacturing were also less than adequate. Filament winding and tape laying machines are the most widely used methods for manufacturing composite components. The FPX will not render either of these processes obsolete, what it will do is fill the role where filament winders and tape layers machine limitations fail specific geometries. The FPX expands the boundaries of composite processing erasing previous impediments to manufacture complex structures from advanced composite materials both efficiently and reliably.

With a wide variety of integrated machine technology, the FPX is able to provide one-step fabrication of symmetrical or asymmetrical, simple or complicated composite structures. Figure 3 illustrates the method by which precise placement of the tow material is achieved to comprise the laminate component. A mechanical compaction roller laminates the tow onto the mandrel or part surface. By mechanically pressing the tows onto the surface, entrapped air and inner band gaps are eliminated. Uniform compaction reduces debulking requirements, processes concave and asymmetrical surfaces, and supports the fiber steering capability. Fiber steering is achieved by differential tow payout speed and compaction, allowing continuous fibers to be directed around openings to eliminate machining or unnecessary buildups. Fiber orientation that is precisely controlled will counter shear stresses heretofore necessarily considered in the design. Fiber steering capabilities are shown in Figure 4. One or more tows are delivered by a method of cut/clamp/restart, programmably controlled individual tows can be started and stopped to precisely place material. The ability to add and drop tows can maintain part boundaries and uniform part thickness by eliminating overlap or increase thickness where the design dictates. This saves valuable material and eliminates manual insertion of material. The combined capability to cut/restart tows with in-process compaction is the first automated method to produce a constant zero degree wind angle on concave or convex structures. Machine tool quality and rigidity and high torque brushless servodrives maintain linear axis repeatability within .002 inches. The FPX uses advanced composite prepreg tow material that in all cases does not exhibit the same tack properties. To conform to different material properties, provisions for variable heating and cooling are incorporated into the delivery head.

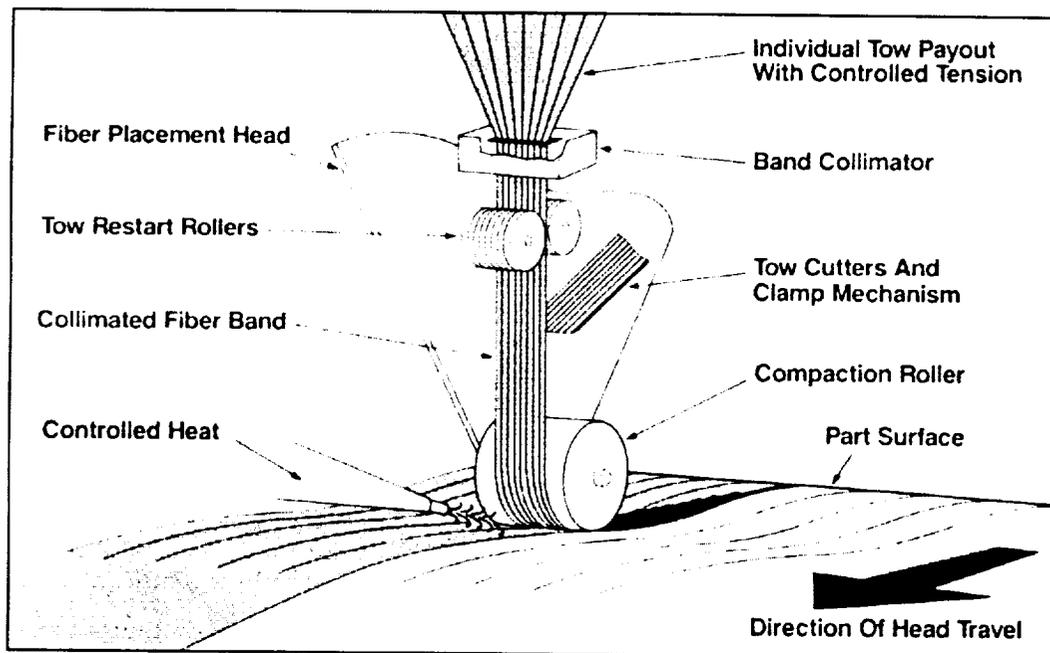
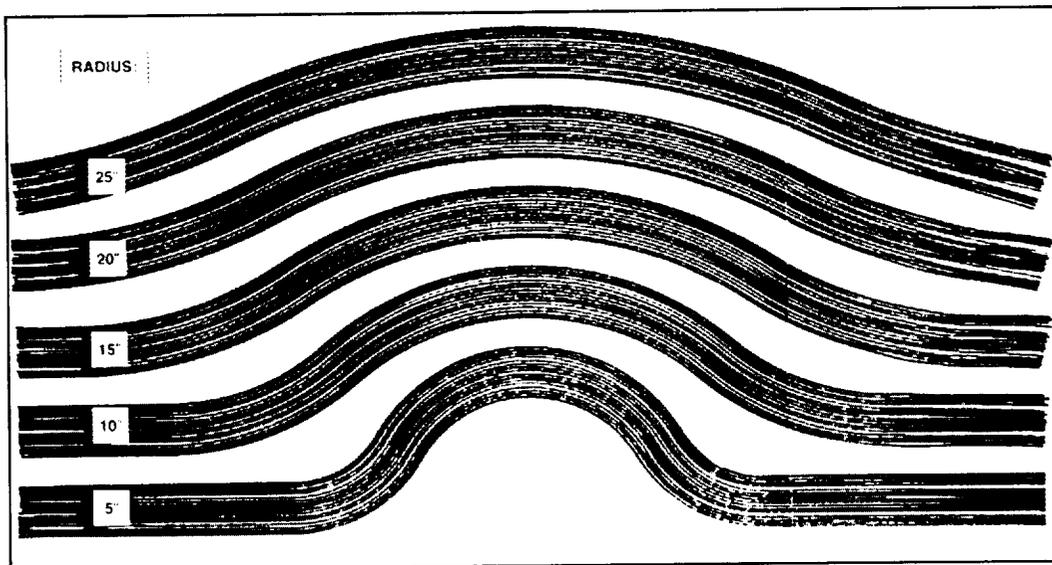


FIGURE 3. FIBER PLACEMENT APPLICATION



**FIGURE 4. FIBER STEERING**

**COST CONSIDERATIONS**

Performance benefits have been the incentive for using composite materials for aerospace applications in that performance has traditionally outweighed cost. Composite structures have a reputation for high cost that is not necessarily deserved. Generally, this misconception stems from comparison of raw material costs with other structural material choices like aluminum; typically prepreg graphite-epoxy can cost seven to ten times more per pound than aluminum. Recent studies however, have integrated total costs for design, manufacturing, assembly and support and in many cases, composites have provided a cost savings as well as the performance benefits. Of the many considerations that affect the cost of composite structures, one of the more important is design. Designers must be educated so that they no longer simply utilize composite materials in aluminum designs. There is a diverse, flexible family of systems available for selection. Automation usually corresponds to lower cost and in the right circumstances this is appropriate. The FPX has feedrates of up to 2400 inches per minute and coupled with in-process compaction, can provide material application rates of over 6 times that of hand layup. Since products are produced with near net shape, scrap rates of up to 40% can be negated. However, problems and discrepancies arise when sophisticated, expensive automated systems are specified for components that could be efficiently manufactured without automation. The choice of fabrication processes for specific composite components should always be thoroughly investigated and with the appropriate strategy, the costs can be significantly less than for equivalent metal components. Concurrent engineering within the design and manufacturing disciplines will ultimately most influence the cost of composite structures.

**MSFC'S FPX MISSION OBJECTIVES  
PROGRAM PLANS**

The multiyear plan for fiber placement consists of a set of programs and activities that will retain and extend our leadership in aerospace manufacturing. The MSFC Fiber Placement System (FPS) is unique and has not been used to fabricate flight quality structures to date. A significant level of confidence will be gained in the manufacturability of these structures. Specific optimal design and manufacturing parameters will be instituted and a database will be established so that other research and flight programs could withdraw information as well as make contributions. This work will transfer the knowledge of technology to an Industry that is avidly awaiting published study results to provide the basis for proposal of composite materials using these manufacturing methods. This study will provide MSFC and Industry manufacturers a baseline understanding of the manufacturing effects on product performance.

### Optical Structures Programs

The use of composite materials for optical bench structures has increased significantly over the last few years. The primary justification for selection of these materials is the ability to maintain precise focal length without thermal control or active focusing systems; coefficients of thermal expansion of zero can be obtained. While structures are successfully fabricated for this application, they are manufactured as one-of-a-kind and primarily by hand. This considerable manual element of the fabrication process reduces repeatability thereby inhibiting analysis and correlation of resultant data. The objective of this research project is to utilize a fully automated processing method to fabricate an optimally designed optical bench. Research associated with optical structures has to date been limited to design and analysis and has not considered the inherent deficiencies of the processing equipment and operator variability. Automation of the fabrication process will reduce processing and operator variability. The optical benches for this study will be designed, manufactured and verified to obtain precise values of axial and radial thermal vacuum expansion. Using current analytical methods, we will develop a model of an optimally designed optical bench that is similar in functional characteristics to an existing design so that its performance characteristics can be compared to existing data for flight hardware. A structure approximately 8.0 inches in diameter, 30 inches in length and .20 inches in wall thickness would correspond to typical structures fabricated in house.

We will use a statistical design of experiments approach to determine the critical processing parameters and interactions that affect the performance of the optical bench. These relationships can be used to develop a prediction equation for determining end performance mean response values. The fiber placement equipment will be used to fabricate test samples and optical bench structures to verify predicted performance characteristics. Mechanical properties and thermal-dimensional stability testing will be conducted to establish performance characteristics.

### RSRM Composite Stiffener Ring

The Redesigned Solid Rocket Motor existing stiffener ring design is inadequate for chance splashdown load conditions that occur unpredictably. A damage condition known a "cavity collapse" may result due to these insufficient structural margins. An investigation is underway to demonstrate manufacturability of a composite replacement stiffener ring to alleviate this problem by increasing these margins with a creative design. The design can be fabricated only manually or with fiber placement. Fabrication of a subscale composite stiffener ring will provides a processing analog to confirm the FPX manufacturing capability.

### Other Programs

The Materials and Process Laboratory manages the Productivity Enhancement Complex at the MSFC, where the composite manufacturing capability resides. Affiliated personnel are continually involved in manufacturing, evaluation and review of existing and planned programs both in house and for contracted efforts. The availability of multiple process methods at the PEC will permit us to perform process comparison studies on specific projects as well as pure investigative studies. Previously we have fabricated the optical benches for the Space Science Laboratory's (SSL) Mission "Multi-Spectral Solar Telescope Array" that was successfully flown May 13, 1991. Also for the SSL optical bench structures were fabricated for the Water Window Imaging X-Ray Microscope. An optical bench was fabricated for the University of Alabama Huntsville's "Newton Telescope" to be used by the Students for the Exploration and Development of Space (SEDS). The Solar X-Ray Imager (SXI) is an MSFC in house project that will require design, development and verification of a flight telescope using a composite optical bench that is deliverable in 1995. Many of the DD&V activities for the Solar X-Ray Imager will directly benefit from these study results. AXAF-S is an earth orbiting X-ray spectrometer that will use a composite optical bench structure also to be fabricated at the PEC. Past MSFC programs that could have benefitted include Hubble Space Telescope and the Soft X-Ray Telescope. We are currently assisting AXAF-I with their evaluation of contracted efforts to fabricate composite optical bench structures. Surveys have indicated that many more programs could benefit from the fiber placement technology: joint IR&D programs, Technology Transfer, and other facility usage agreements have been proposed by government and aerospace contractors. Each of these programs will be evaluated so that appropriate priorities can be determined.

## CONCLUSION

The FPX is a prominent addition to the MSFC in house advanced technology facilities. To augment this capability, the proposed work and other research programs will strengthen our in-house expertise and showcase our can-do-ability. With continued emphasis on the MSFC's composite manufacturing capability, we will confirm and retain a world class status. Since technology is a vital ingredient in the Nation's economic competitiveness, it is clear that it will continue to be one of NASA's principal goals to achieve technology transfer, and do it largely through direct interactions between researchers and engineers. Fundamental research and employment of innovative concepts like fiber placement will provide a continuum of technological development for America's space program. By committing ourselves and our resources to restoring our Nation's technology base, we can assume and maintain the leadership in many key industries.

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